Linear Colliders:
Achieving High Luminosity

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Outline:

- Luminosity: high beam power, small beam size
- Generation, acceleration, and transport of low emittance, high power beams
- Conclusion

Generic features of all linear colliders:

- Injector
  - (Polarized) electron and positron sources
  - Damping rings
  - Bunch compressor
- Main linac
- Beam transport to final focus and interaction point

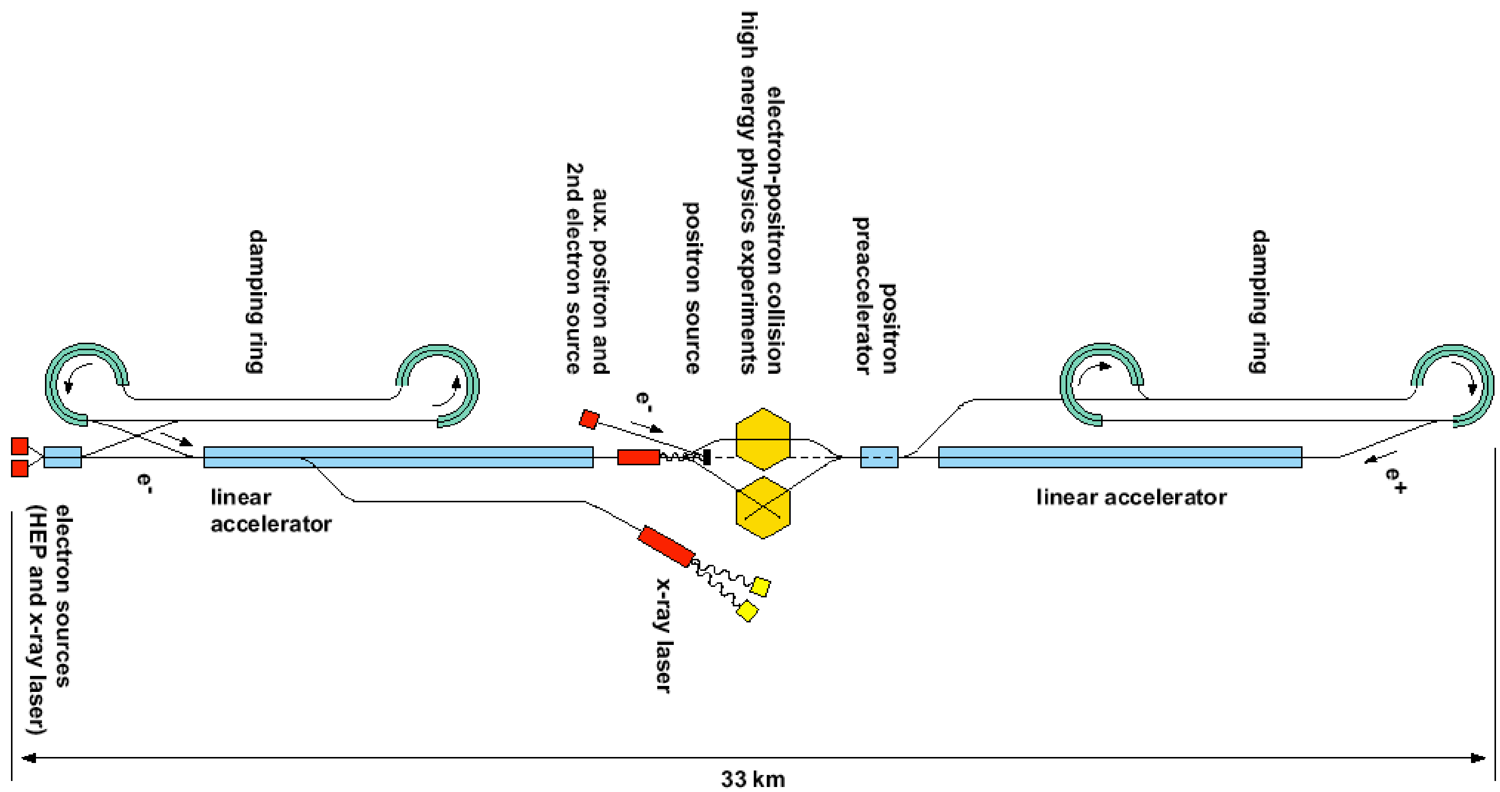


Figure 1.2.1: *Sketch of the overall layout of TESLA.*

TESLA Linear Collider
Superconducting RF 1.3 GHz, 35 MV/m

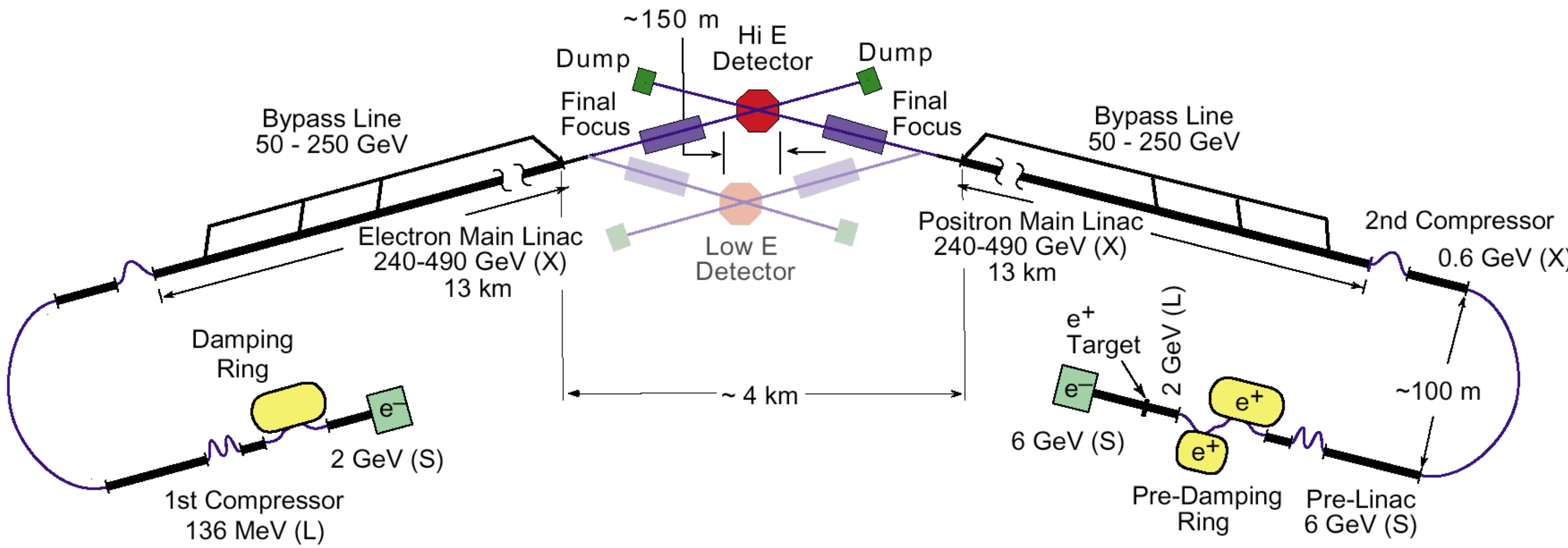


Figure 1.1: Schematic of the JLC/NLC

NLC-JLC Linear Collider
Warm RF 11.4 GHz, 70 MV/m

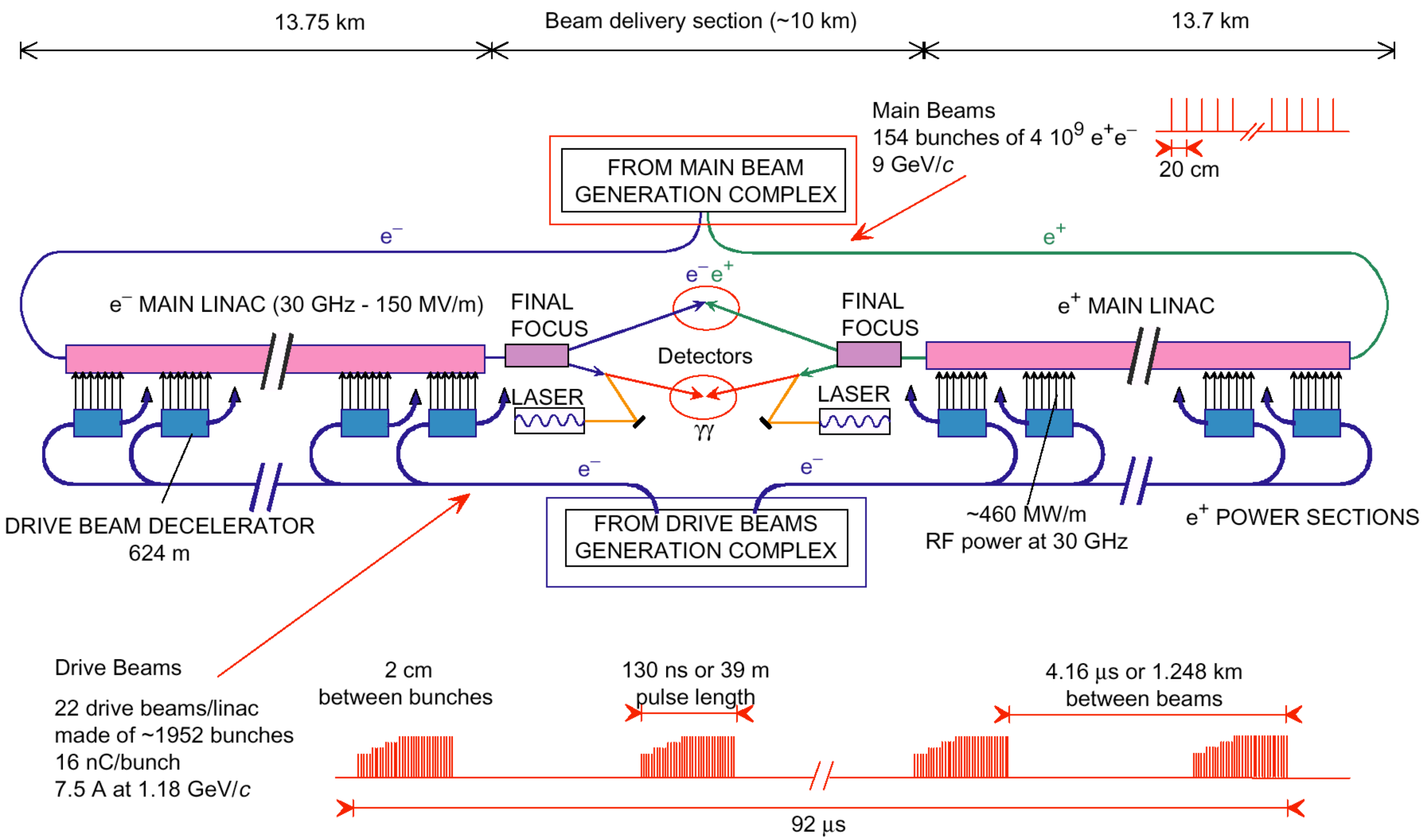


Fig. 1.1: *Overall layout of CLIC for a centre-of-mass energy of 3 TeV.*

CLIC Linear Collider
Warm RF 30 GHz, 170 MV/m, two-beam

Linear collider luminosity

Beam power

Transverse density

$$L = \frac{P_b}{4\pi E_b}\left(\frac{N}{\sigma_x \sigma_y}\right)$$

Bunch population

Beam energy

Rms horizontal beam size at the IP

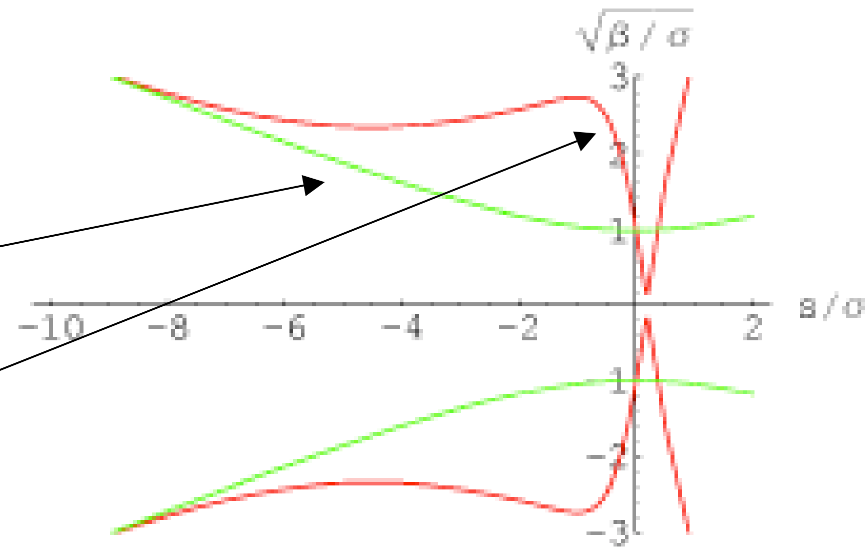
Rms vertical beam size at the IP

Very high transverse densities encounter limitations due to the beam-beam interaction

When dense beams collide

Beam envelope
w/o beam-beam

Beam envelope
with beam-beam



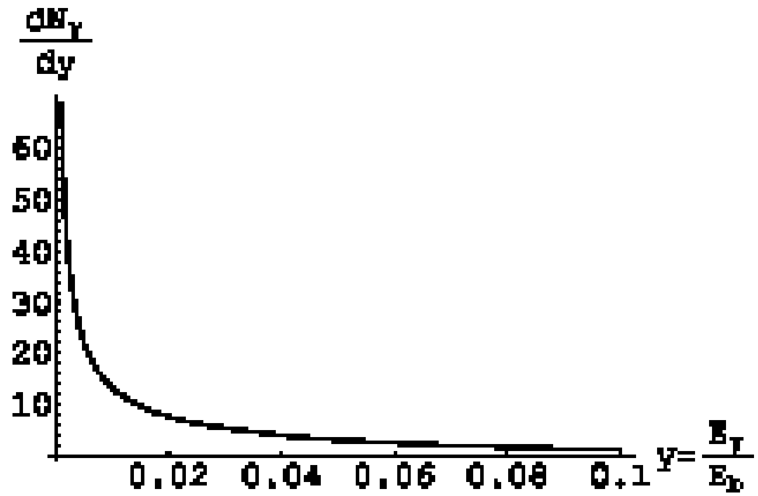
Beam-beam interaction: the strong electromagnetic fields of the opposing bunch produce:

1. Pinch ("disruption"): a luminosity enhancement factor H_D

2. Radiation ("beamsstralung"): a source of background and energy spread

Beamsstralung photons per electron $N_\gamma \approx 2\frac{\alpha r_e N}{\sigma_x + \sigma_y}$

Photon number spectrum:



To limit background and keep the energy spread under control, N_γ should not exceed 1-2. Since

$$\frac{L}{N_\gamma} \propto \frac{1}{\sigma_x} + \frac{1}{\sigma_y}$$

all the LC designs use **flat beams** $\sigma_y << \sigma_x$

Linear collider luminosity parameters

$$L\left[10^{34}\ \mathrm{cm}^{-2}\mathrm{s}^{-1}\right] \approx 121\left(N_{\gamma} H_{D}\right)\frac{P_b[\mathrm{MW}]}{E_b[\mathrm{GeV}]}\frac{1}{\sigma_y[\mathrm{nm}]}$$

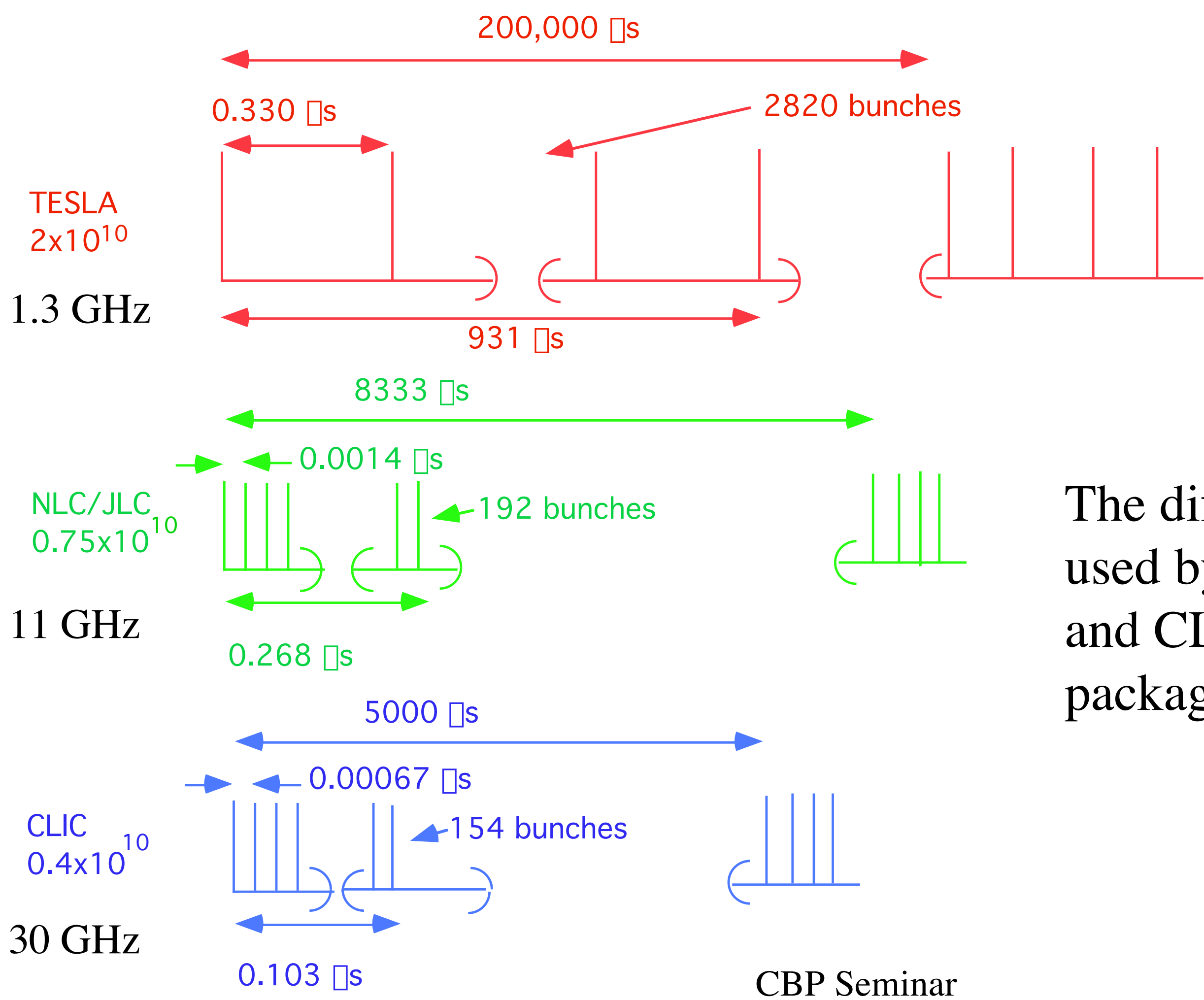
Parameter	SLC	TESLA	NLC/JLC	CLIC
Beam energy [GeV]	46	250	250	250
Beam power [MW]	0.035	11.3	6.9	4.9
Vertical rms beam size at IP [nm]	650	5	3	2.5
Beamsstralung photons/electron N_{γ}	1.1	1.6	1.3	0.7
Disruption enhancement H_D	2.1	2.1	1.5	2.6
Luminosity (10^{33} cm^{-2} s^{-1})	0.003	34	20	18

Achieving high luminosity

- **Maximize the beam power**-
  - Limited by the wall plug power and rf -> beam power efficiency
- **Minimize the vertical beam size at the IP**
  - Limited by the beam emittance provided by the injector, emittance dilution in the linac, and the final focus optics.
- **Stabilize the vertical beam position at the IP**
  - Limited by component physical motion (natural ground motion, man-made sources) and EM field fluctuations

Achieving high luminosity

• **Maximize the beam power**- It is limited by the wall plug power and rf -> beam power efficiency



The different RF technologies used by TESLA, NLC/JLC and CLIC require different packaging for the beam power

Beam size parameters-500 GeV CM

Vertical beam size at IP: $\sigma_y = \sqrt{\frac{\varepsilon_y}{\gamma}\left(\beta^*_y\right)}$

Parameter	TESLA	NLC/JLC	CLIC
Vertical rms emittance from DR [μm]	0.02	0.02	0.003
Vertical rms emittance at IP [μm]	0.03	0.04	0.02
Vertical β at IP [mm]	0.4	0.11	0.15
Vertical rms beam size at IP [nm]	5	3	2.5
Rms bunch length at IP [mm]	0.3	0.11	0.03
Rms energy spread at IP [%]	0.14/0.04	0.25	
Luminosity (10^{33} cm^{-2} s^{-1})	34	20	18

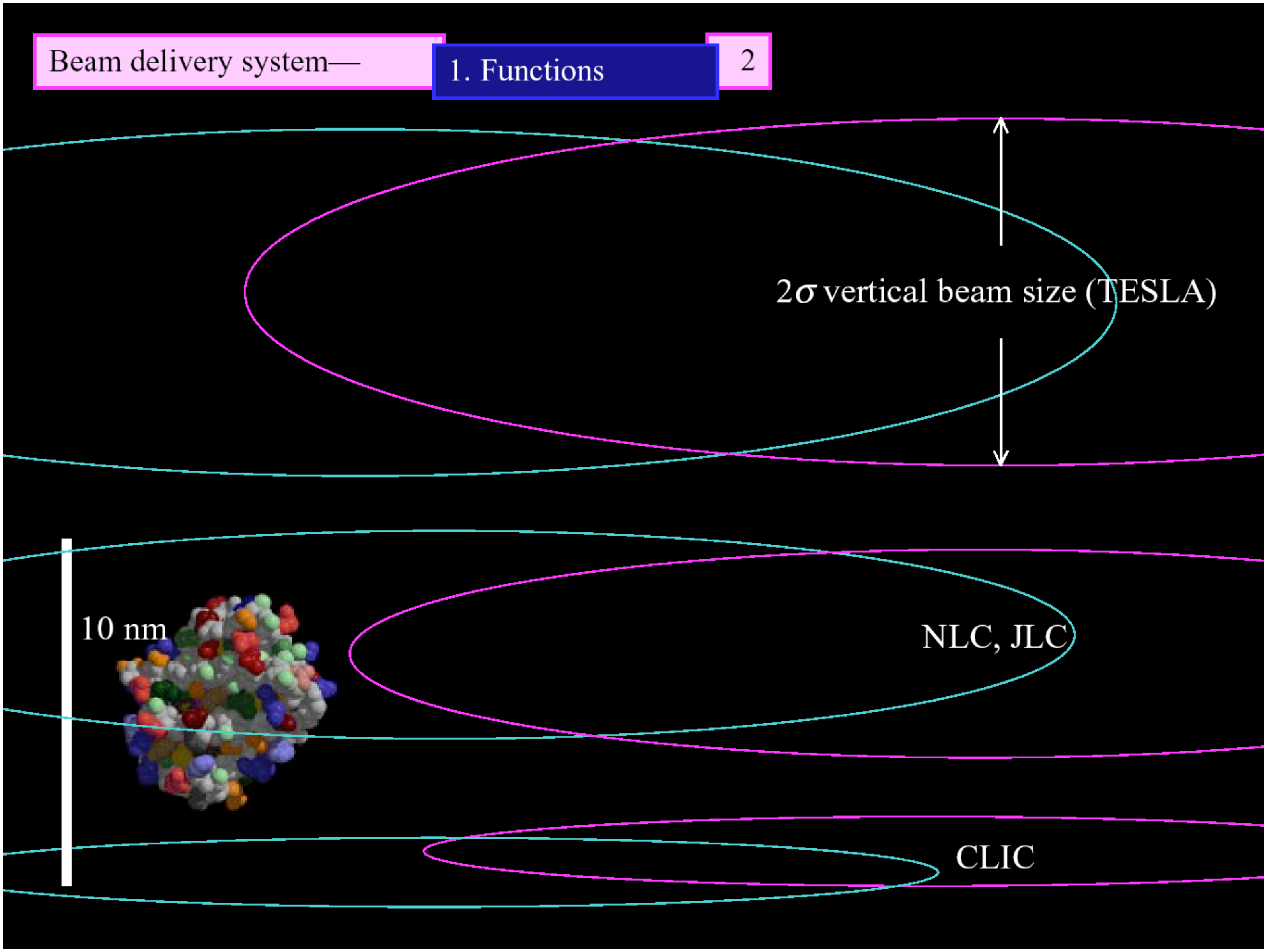
Beam spot size at IP $\sigma^2=\beta\varepsilon_n/\gamma$

Parameter	Required NLC	Required TESLA	Achieved FFTB	Achieved ATF
β (mm)	0.1	0.4	0.1	
ε_n (μm)	0.04	0.03	4.6	0.077
σ (nm)	3	5	70	

IP vertical beam sizes in some other machines:

Tevatron (1000 GeV): σ =86,000 nm

LEP (100 GeV): σ =3,300 nm



J Rogers, Cornell

Generating and accelerating low emittance beams

- Particle sources:
  - produce the electrons and positrons
- Damping rings:
  - reduce the beam emittance
- Linacs:
  - Accelerate the beams while preserving the small emittance
- Transport and final focus:
  - Deliver the beams to a tight focus at the IP, with minimal jitter

Electron and positron sources

- Electron sources
  - DC polarized photocathode guns
  - Polarization >80%, normalized transverse rms emittance ~50-100 μm, round beam
- Positron sources
  - Conventional (NLC/JLC, CLIC): Bombard a thick high-Z target with a few GeV electron beam, collect positrons from shower
  - Undulator based (TESLA): Use ~20 MeV gamma radiation from a very high energy electron undulator to produce positrons in a thin low-Z target
  - Normalized transverse edge emittances ~30,000 μm, round beams

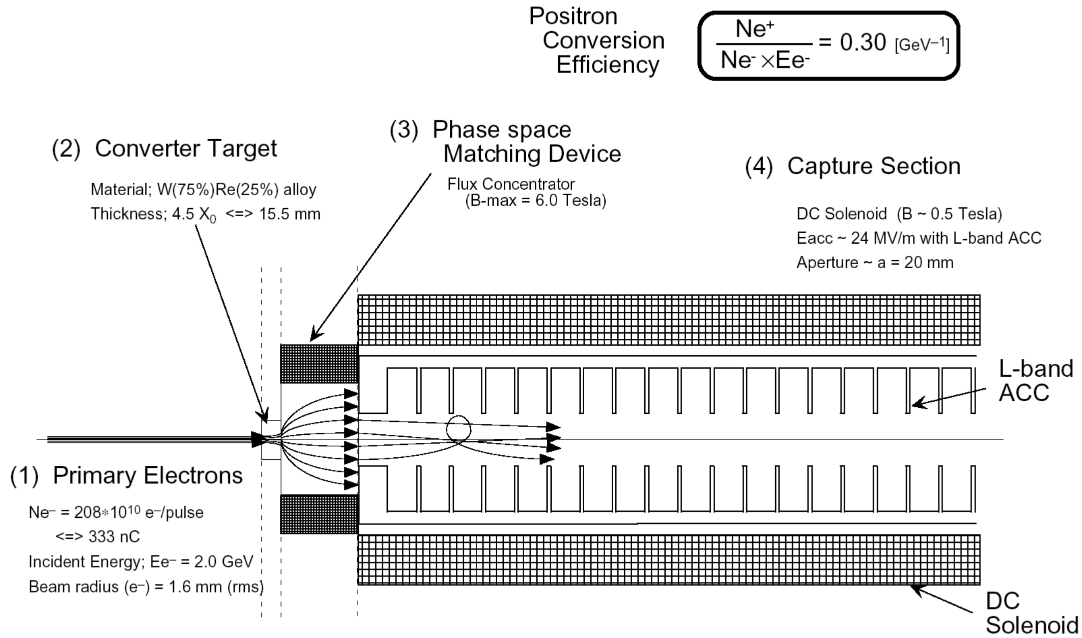


Figure 4: CLIC e^+ generator

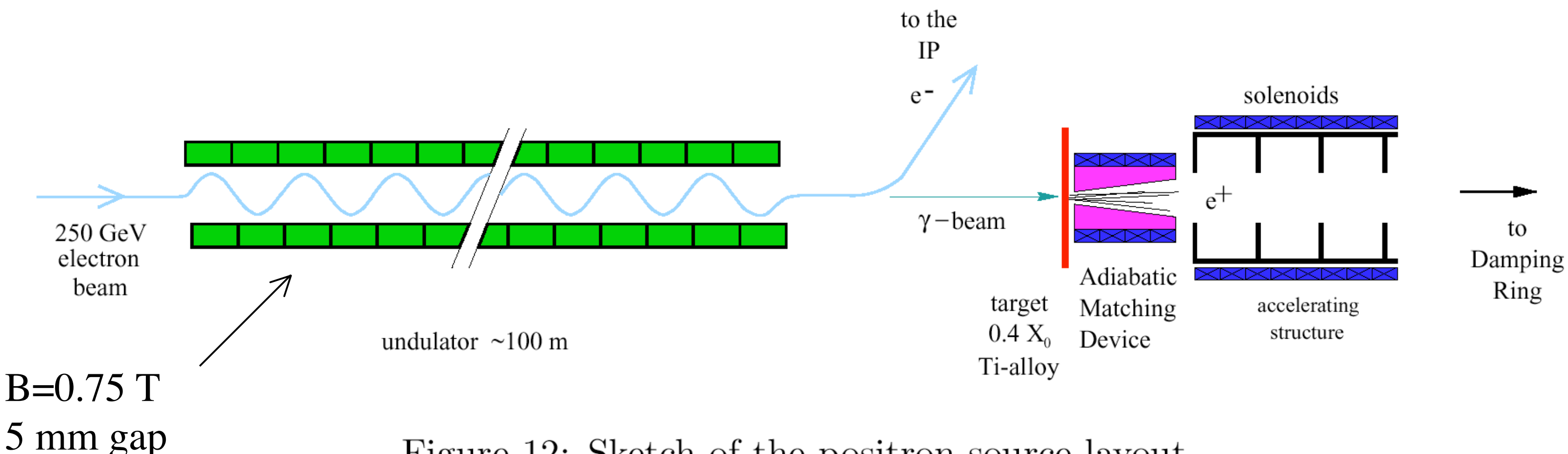
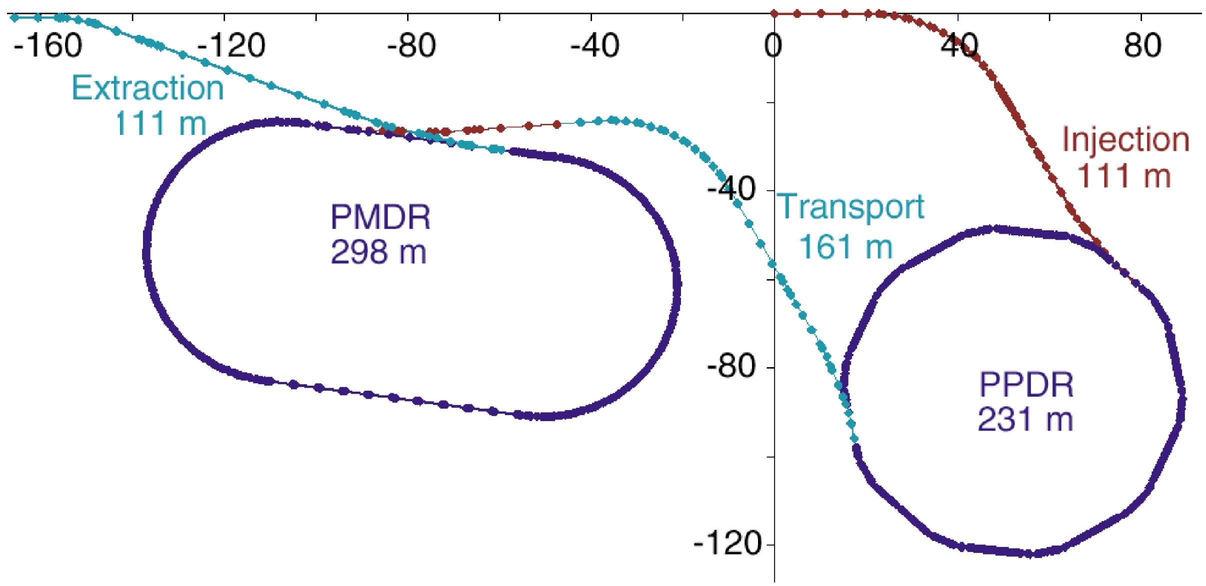


Figure 12: Sketch of the positron source layout.

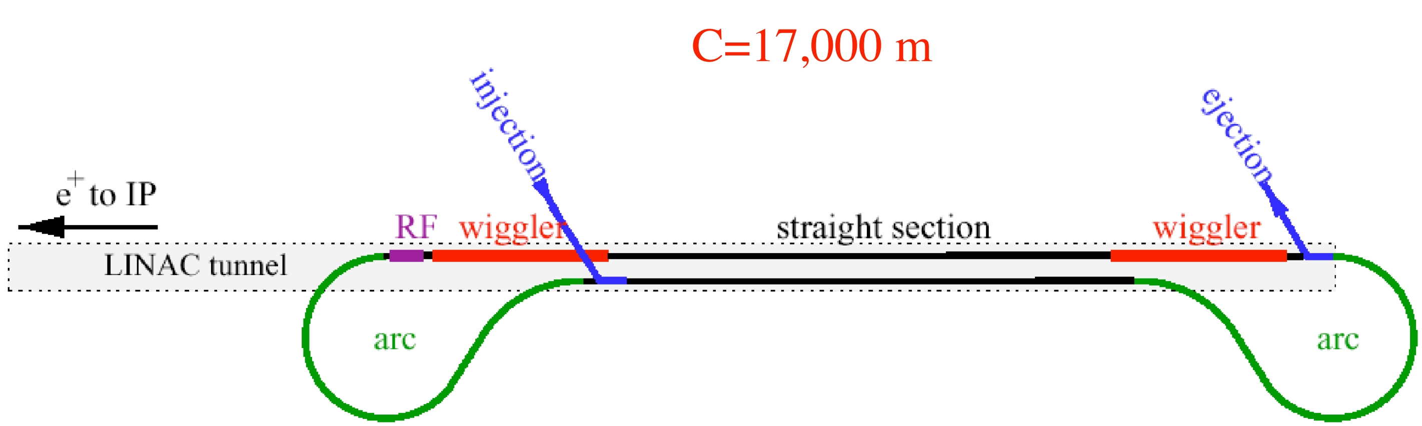
Generating low emittance beams: damping rings:

- The very small emittance beams required for high luminosity result from synchrotron radiation damping in specially designed *damping rings*.
- Damping rings must store several bunch trains for several damping times (a few tens of milliseconds). In TESLA's case, the long bunch train necessitates a very large circumference ring.

NLC positron pre-damping ring (PPDR) and main damping ring (PMDR).



TESLA DR layout (the “dog-bone”)



Linear collider damping rings

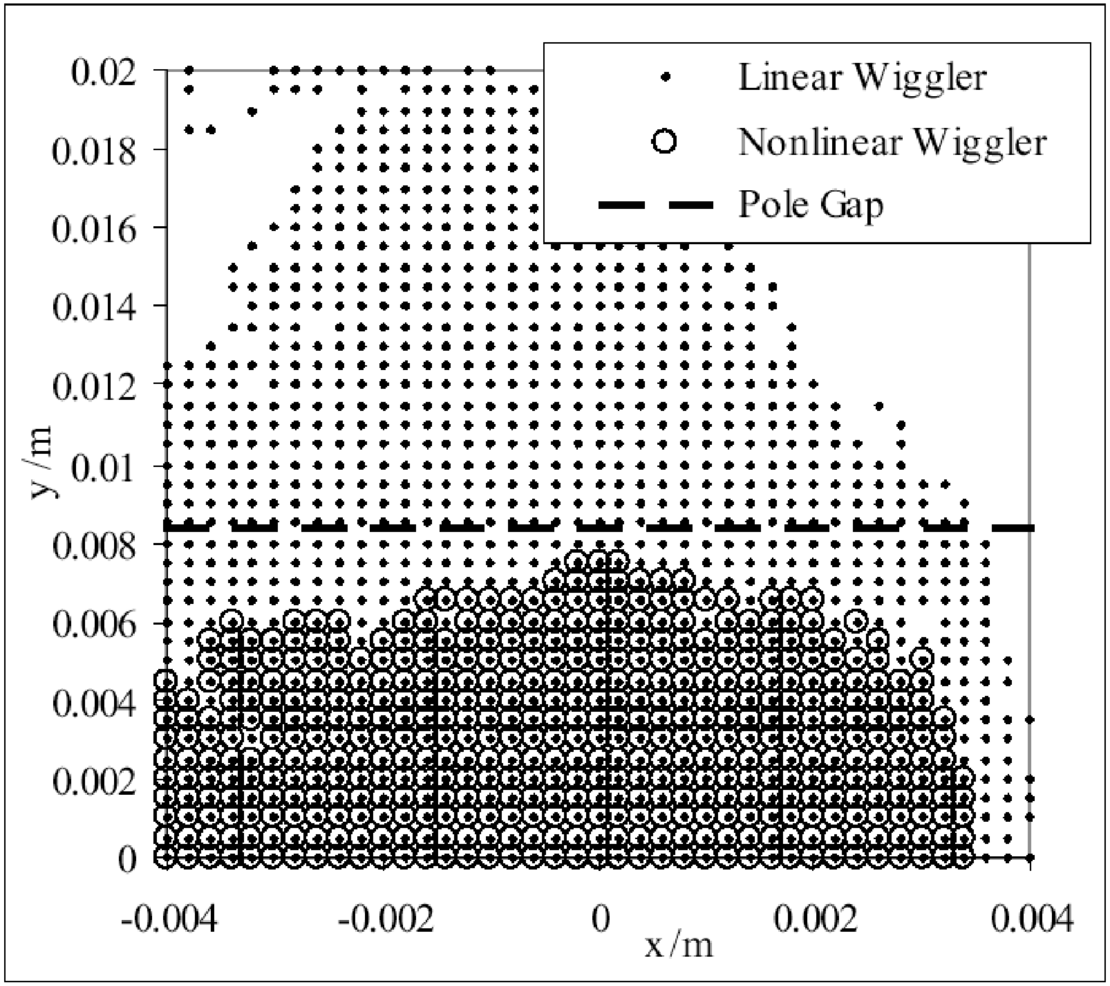
Lattices:
NLC/JLC: TME (theoretical minimum emittance cells) with 46 meters of 2.15 T permanent magnet hybrid wigglers in dispersion-free straight sections.

TESLA: TME (theoretical minimum emittance cells) with ≈400 meters of 1.67 T permanent magnet hybrid wigglers in dispersion-free straight sections.

Most of the DR is a long straight section. Vertical space charge tune shift *would* be large ($\Delta Q_y \approx 0.23$), so the beam is intentionally x-y coupled at the beginning of the straight, and uncoupled again at the end, to make a large vertical beam size in the straight, producing $\Delta Q_y \approx 0.035$.

Some damping ring issues

- Magnetic lattice design for low emittance and rapid damping: extensive use of wiggler magnets. The dynamic aperture is limited primarily by sextupole and wiggler nonlinearities.
- Emittance growth control: intrabeam scattering (IBS), space charge effects, and beam gas scattering must be limited.
- Instabilities-interaction of the stored beams with ions generated by ionization of the residual gas (fast ion instability), or (for positrons) with photoelectrons generated by the synchrotron radiation (electron cloud).
- Beam jitter: Ground motion and vibration of ring magnets must be controlled; extraction devices must be very stable.



A.Wolski, J.N. Corlett, Y. Wu, PAC01

Dynamic aperture calculations for the NLC MDR

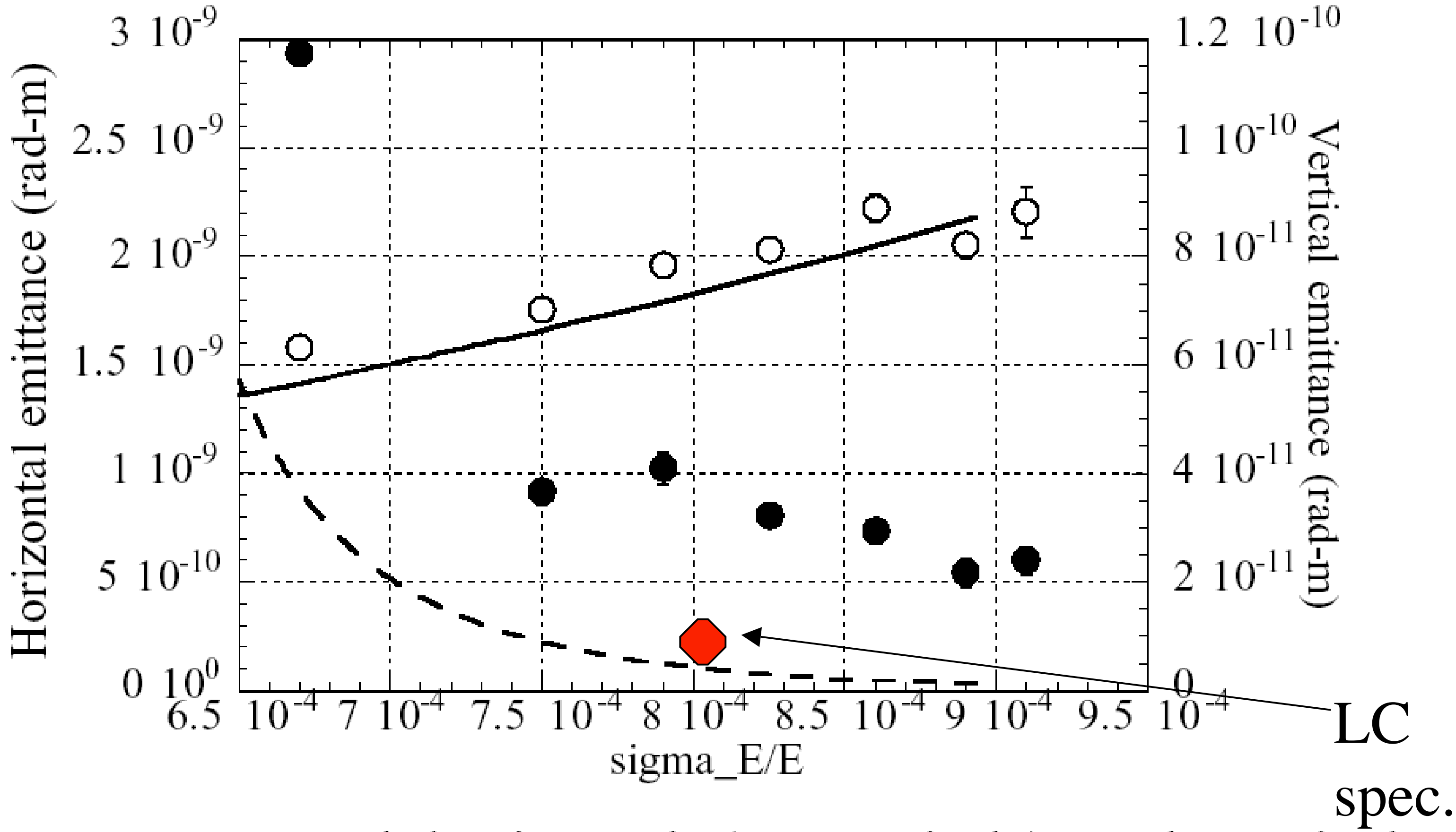
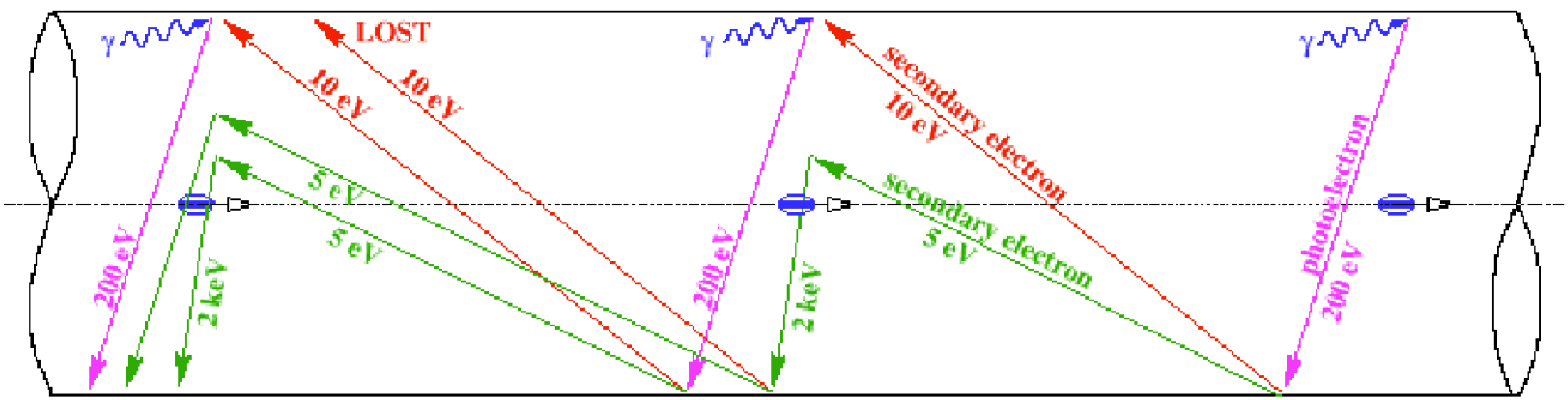


Fig. 8, Measured horizontal (open circle) and vertical (filled circle) emittance vs. energy spread. Lines are from calculation of intra-beam scattering.

IBS Measurements at the KEK ATF: K. Kubo, HEACC2001

Electron cloud instability: electrons produced by photoemission or residual gas ionization are accelerated toward the chamber wall by the electric field of a positron bunch

- ➥ Secondary emission and multipacting
- ➥ Large background of electrons
- ➥ Head-tail and bunch-to-bunch coupling
- ➥ Instability



F. Ruggiero, CERN

Countermeasures: reduce secondary yield, use clearing electrodes, use fast feedback

Acceleration and collision of low emittance beams

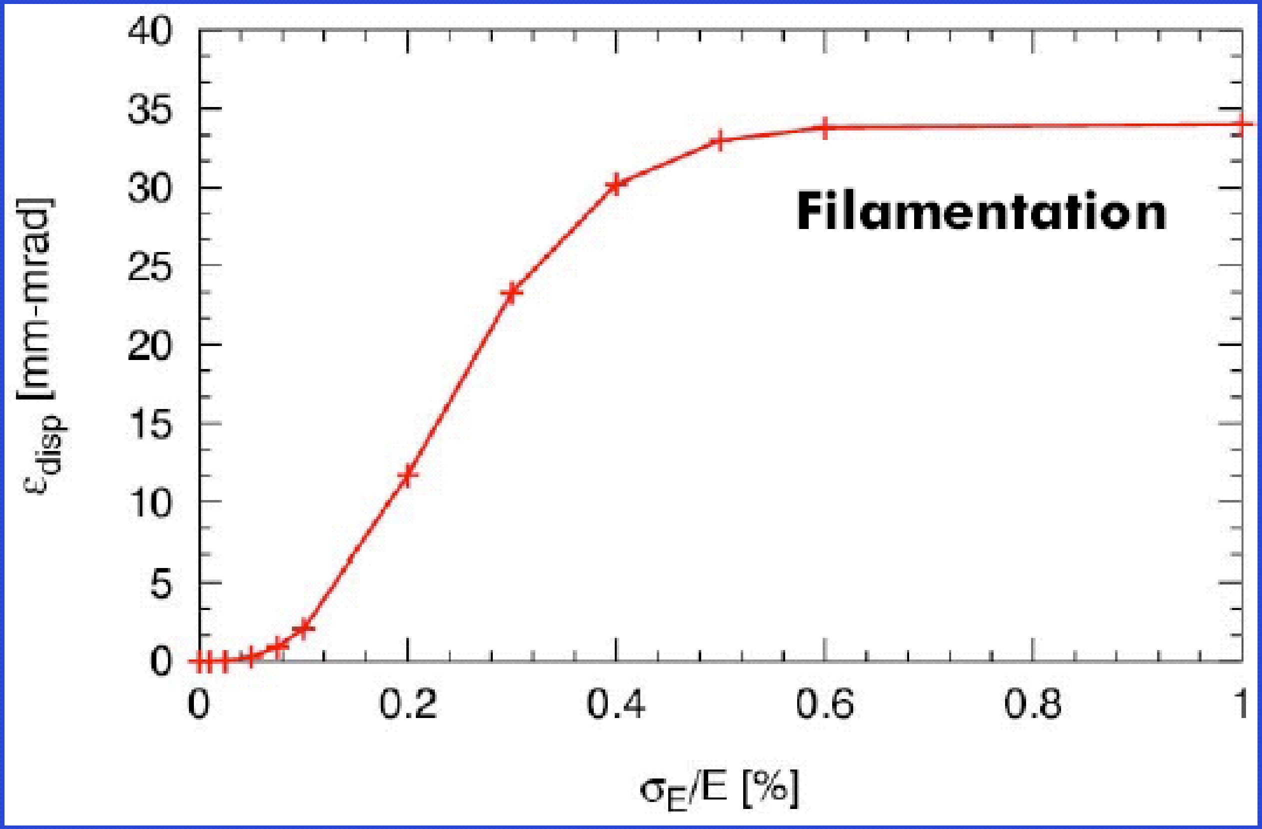
- To achieve high luminosity, very small vertical emittances must be accelerated in very long linacs with small emittance growth (~0.01 □m) and small beam jitter (~0.1□).
- Sources of emittance growth:
  - Dispersive emittance growth
  - Wakefield induced emittance growth
- Sources of beam jitter:
  - Injection errors
  - Component vibration (ground motion)

Dispersive emittance growth

- Particles with different momenta follow different trajectories in a field. A beam with a finite energy spread will be dispersed. Even if the magnetic design is achromatic at the interaction point, since the required beam size is so small, even very small dipole field errors can cause a significant growth of the beam size and loss of luminosity.
- The dominant source of such errors is quadrupole position misalignments. Injection errors and component jitter are other sources.

Sensitivity to dispersion

Example case CLIC type – no acceleration – no wakefields
QD misaligned by 50 μm



From R. Assmann, CERN

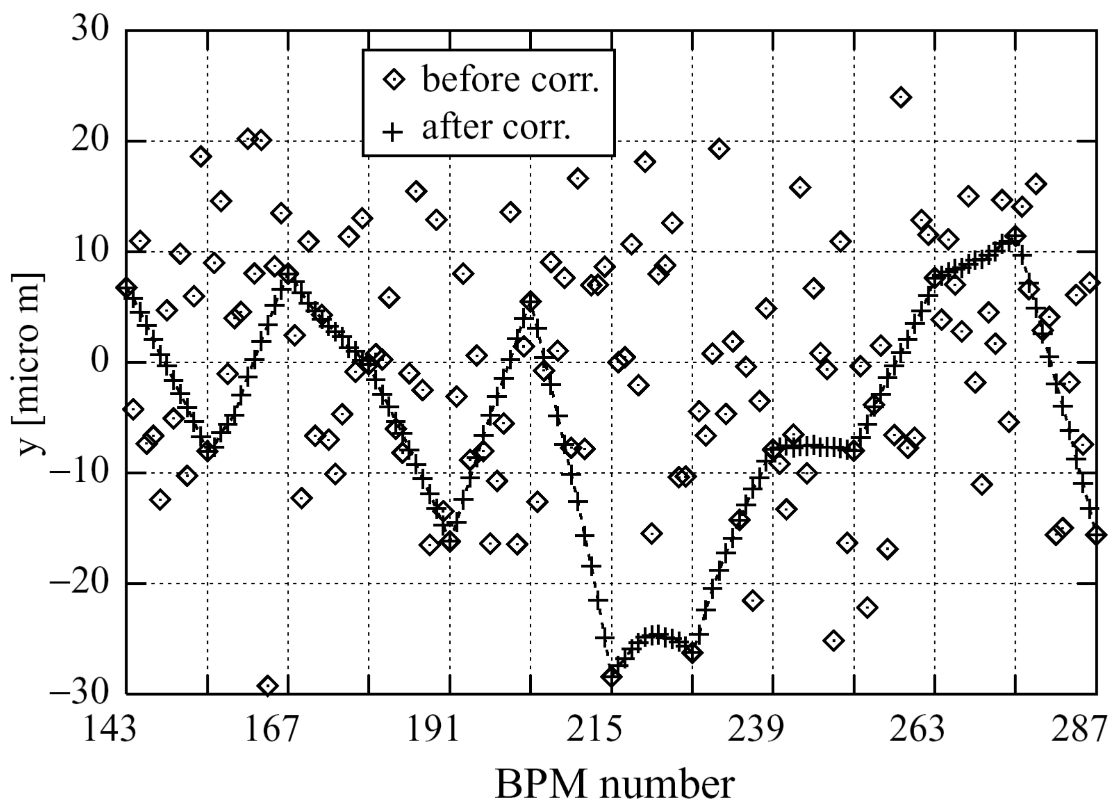
Emittance saturates due to filamentation for large energy spread
(chromatic phase mixing)

Control of dispersive emittance growth

- **Quadrupole position alignment at the micron level is required. The initial survey cannot be done with sufficient accuracy to satisfy this requirement. Additionally, diffusive ground motion will produce misalignments of this scale after a few days.**
- The beam itself must be used to find the centers of the quadrupoles: "beam-based alignment"
- The limitations to beam-based alignment are principally systematic errors, such as finite BPM resolution, beam jitter, motion of a quadrupole's center with the quadrupole's strength, etc.

Ballistic alignment: Divide beam line into bins with 12 quads each. Switch off all quads but one, steer to last BPM, align all other BPM's in bin to the beam. Switch on quads, align to BPMS's

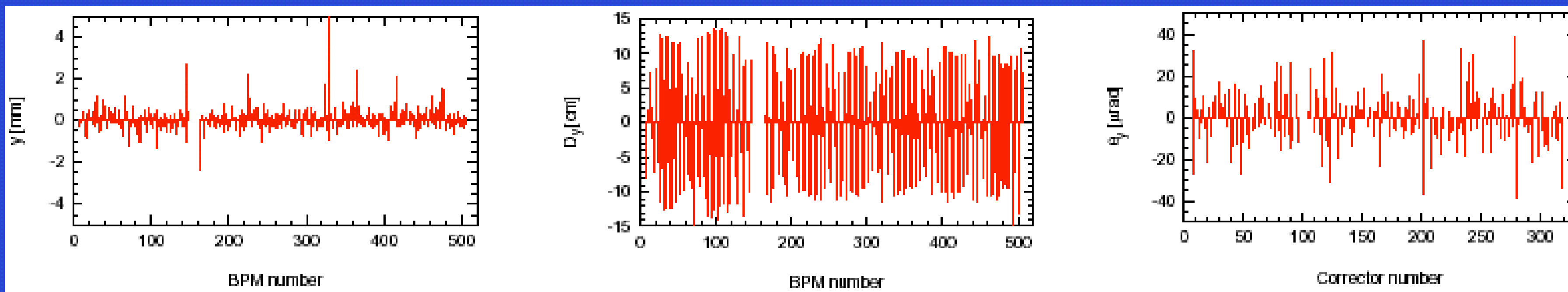
From CLIC design study:



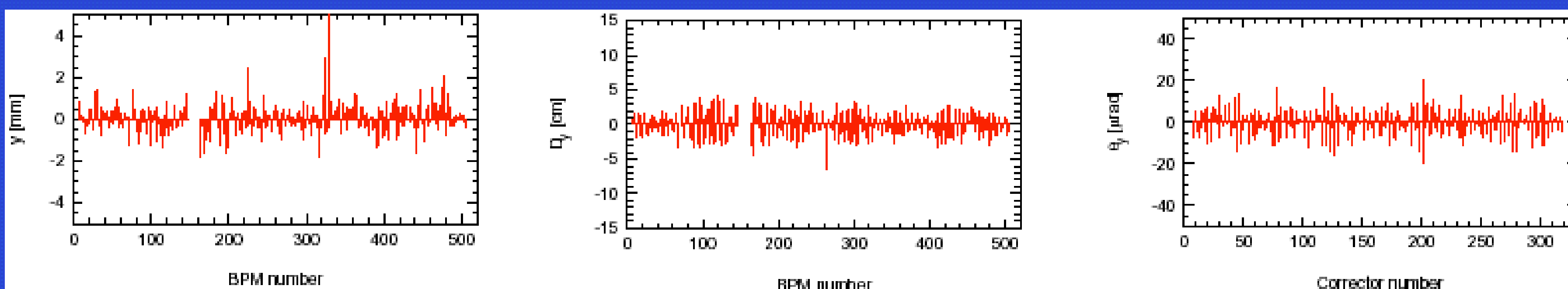
From R. Assmann, CERN

Dispersion free steering at LEP

ORBIT | DISPERSION | CORR. KICKS



DFS: ⇩ Simultaneously ⇩ optimize orbit, disp., ⇩ corr.



Suggested for NLC (Raubenheimer et al). Developed for SLC (Assmann et al)!

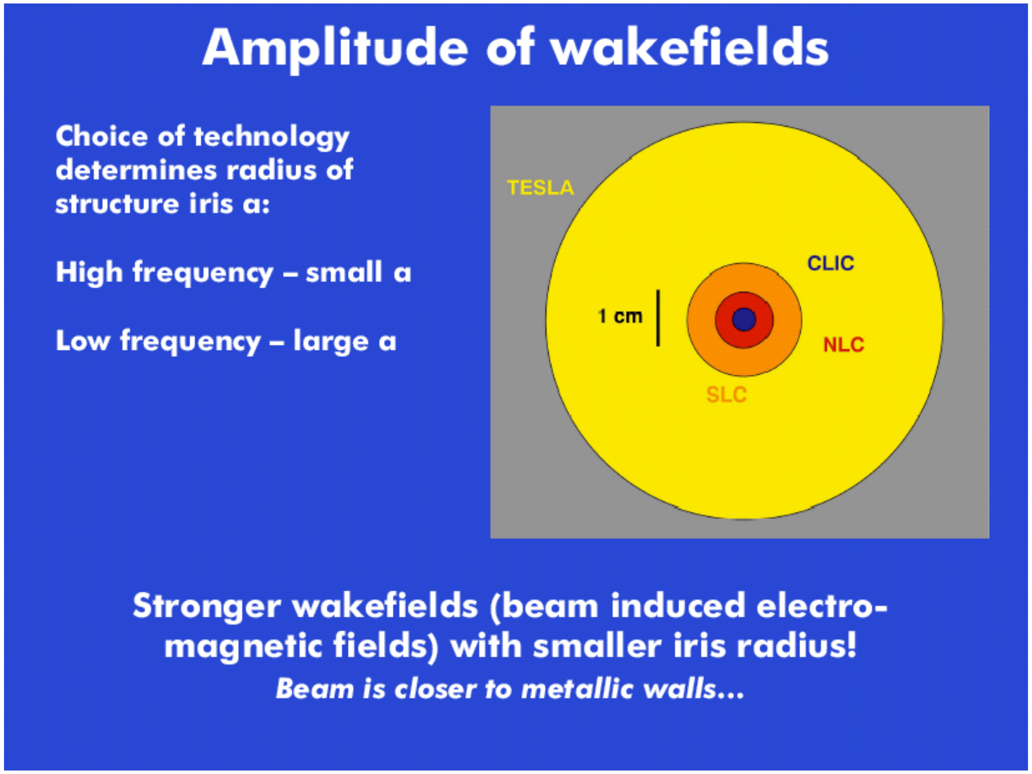
It even works for storage rings... (it should work for future LC!)

Wakefield induced emittance growth

• The RF structures in the linac have dipole deflecting modes as well as the fundamental longitudinal accelerating mode. An electron traveling through a structure can excite these modes, which will create deflecting and decelerating fields ("wakefields") that perturb subsequent electrons.

• Short-range wakefields couple the tail of on bunch to its head; the head and tail no longer follow the same orbit, so the effective beam size at the IP will be larger.

• Long range wakefields couple bunches together: not all bunches follow the same orbit, so they do not all collide head-on with their counterparts.



From R. Assmann, CERN

The different linear collider designs have very different RF structures and very different wakefields.

(wakefields quoted below are at 1 σ, in V/pC/m^2)

Parameter	**TESLA**	**SLC**	**NLC**	**CLIC**
RF frequency (GHz)	1.3	2.8	11.4	30
Transverse wakefield W	22	1990	11460	81000
Bunch population N (10^{10})	2		0.75	0.4
Average vertical beta β_v	120		50	35
Relative betatron amplitude ~ W N β_v	5000		430,000	1,130,000

Control of wakefield induced single-bunch emittance growth

- Wakefields will produce emittance growth whenever the beam passes off-axis through an RF cavity.
- The two principal causes of this are
  - Injection errors
  - Cavity misalignments

Control of wakefield induced single-bunch emittance growth

- The development of head-tail growth due to coherent oscillations at injection is controlled through the use of "BNS damping": this is the establishment of a tune difference between the head and tail of the bunch, which suppresses the resonant driving of the tail.
- The tune difference is typically established by phasing the bunch off-crest in the rf wave, which results in a difference in energy between the head and the tail. The dependence of the tune on energy (chromaticity) then produces a tune difference between the head and the tail.
- The required energy spread, however, makes the dispersive effects noted above worse.

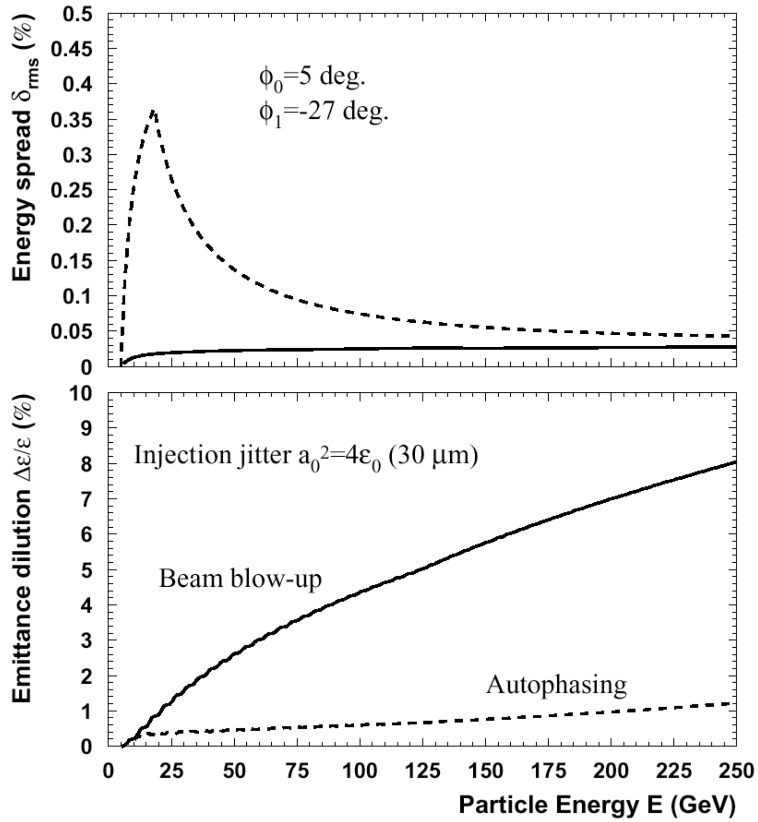


Figure 9: Illustration of BNS damping in TESLA. The correlated energy spread (dashed curve in upper figure, full curve without BNS) is generated in the 5 to 25 GeV section of the linac and the beneficial effect is shown in the dashed autophasing curve.

Control of wakefield induced single-bunch emittance growth

- Rf structure misalignments are minimized by the use of "structure BPM's" which measure directly the beam offset in the rf structure.
- The remaining residual effects may be partially cancelled by the introduction of "non-dispersive bumps" which produce wakefield effects which just cancel those of the structure misalignments.
- To tune the bumps: must measure the emittance-> laser wires. Beam size at □=50 m is about 1 micron->want to measure size to 10%, need resolution of 100 nm=>laser interferometer devices (resolution 60 nm seen at FFTB)

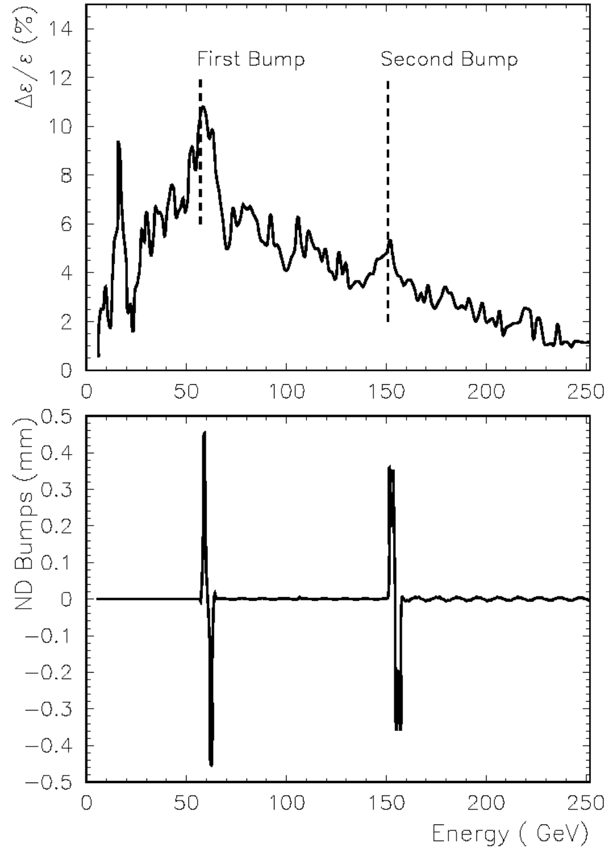


Figure 10: Example of (non-dispersive) wakefield correction bumps for one particular random seed of misalignments. With two bumps, the emittance growth is reduced by one order of magnitude.

Non-dispersive bumps in TESLA

Requirements for control of single bunch emittance growth

- Tolerance/instrumentation requirements:

Machine	Quad BPM resolution	BNS energy spread	Structure misalignment	Structure BPM resolution
TESLA	10 μm	0.35%	300 μm	
NLC/JLC	0.3 μm	0.8%	30 μm	5 μm
CLIC	0.1 μm	2%	10 μm	

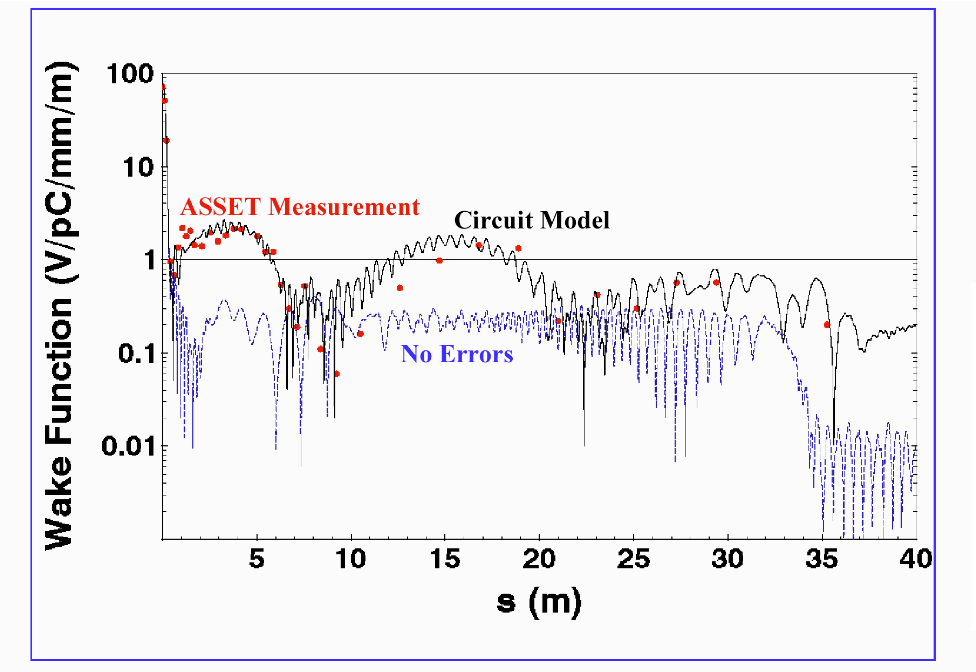
- Estimated resulting emittance growth:

Machine	Static Quadrupole misalignments, after orbit correction with DFS	Transverse wakes from structure misalignment, after ND bumps
TESLA	2%	2%
NLC/JLC	25%	7%
CLIC	Small	22%

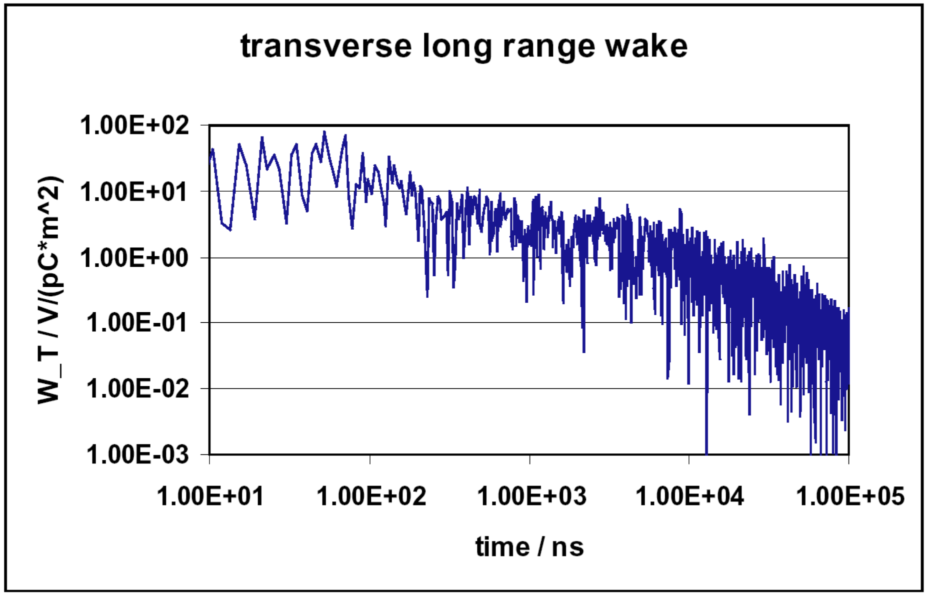
Control of multi-bunch emittance growth due to long-range wakefields

- Emittance growth due to long range wakes is controlled by RF structure design methods which suppress the effects of dipole modes.
  - For the warm RF systems, this is done by a combination of detuning of the cell dipole modes along the length of a multi-cell cavity, together with damping manifolds which couple out the dipole modes.
  - For TESLA, this is done using dipole mode dampers located at the ends of each 9-cell cavity.
- Great care is required in construction of the RF structures: e.g., NLC/JLC structure dipole mode cell frequency variation should be limited to ~few MHz out of 15 GHz

NLC RDDS wake

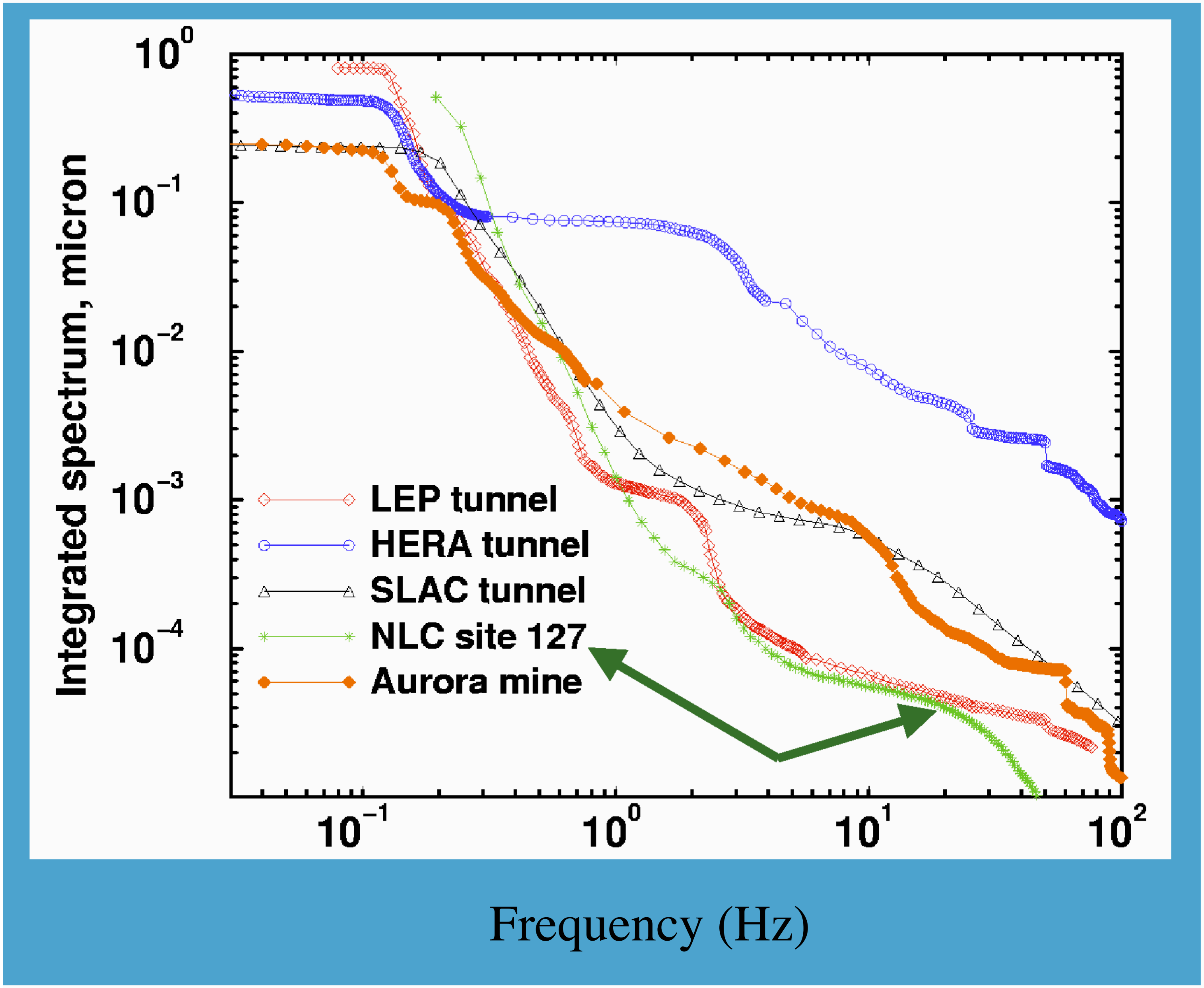


TESLA 9-cell cavity wake



Threats to luminosity from the motion of components

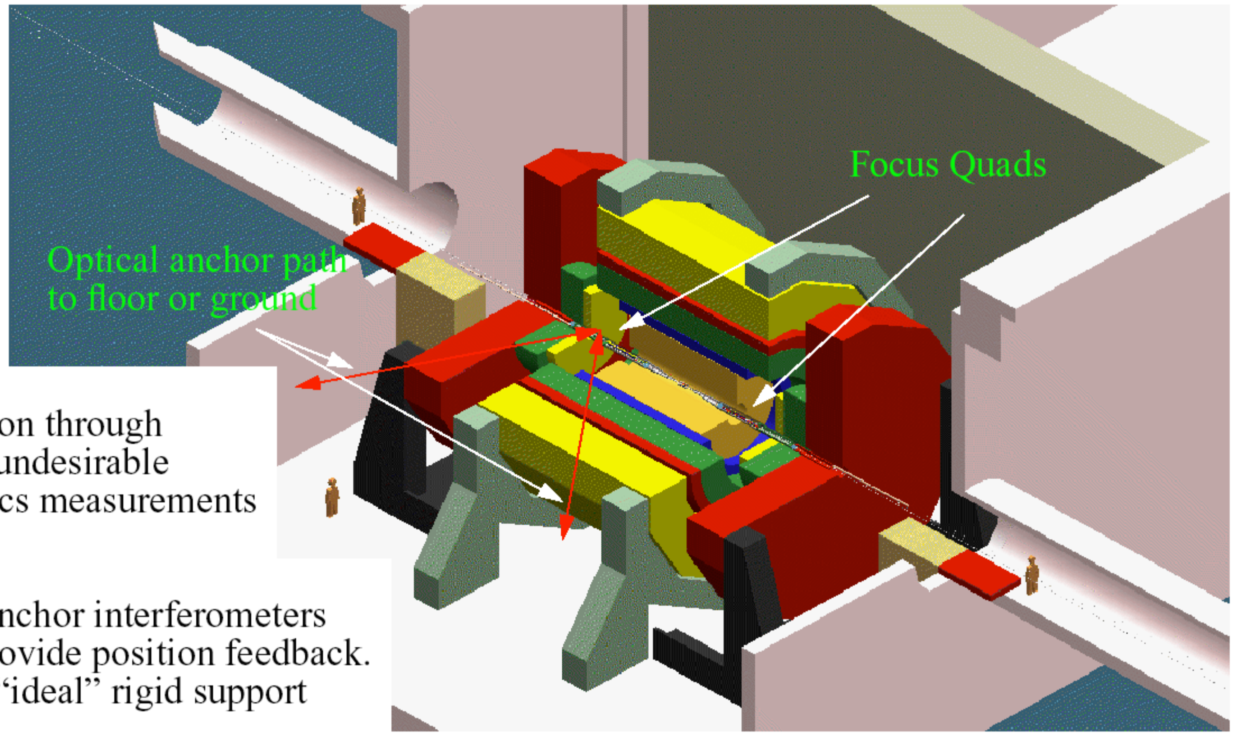
- High frequency component motion (time scale of seconds and less) can cause the beams to miss at the collision point. Tolerance is at the 0.1□ level: tens to hundreds of nm in the linacs, 1 nm in the final focus.
- Natural ground motion at these frequencies is ~10 nm: OK for linacs, but final focus system needs active stabilization.
- At lower frequencies (< 1 Hz) ground motion is larger but tends to be highly correlated (long-wavelength), so the tolerance is greater.


Integrated spectrum, micron
10^{0}
10^{-1}
10^{-2}
10^{-3}
10^{-4}
LEP tunnel
HERA tunnel
SLAC tunnel
NLC site 127
Aurora mine
10^{-1}
10^{0}
10^{1}
10^{2}
Frequency (Hz)

Optical Anchor

It is impossible to rigidly mount the magnets to the ground. Instead use interferometer for position feedback

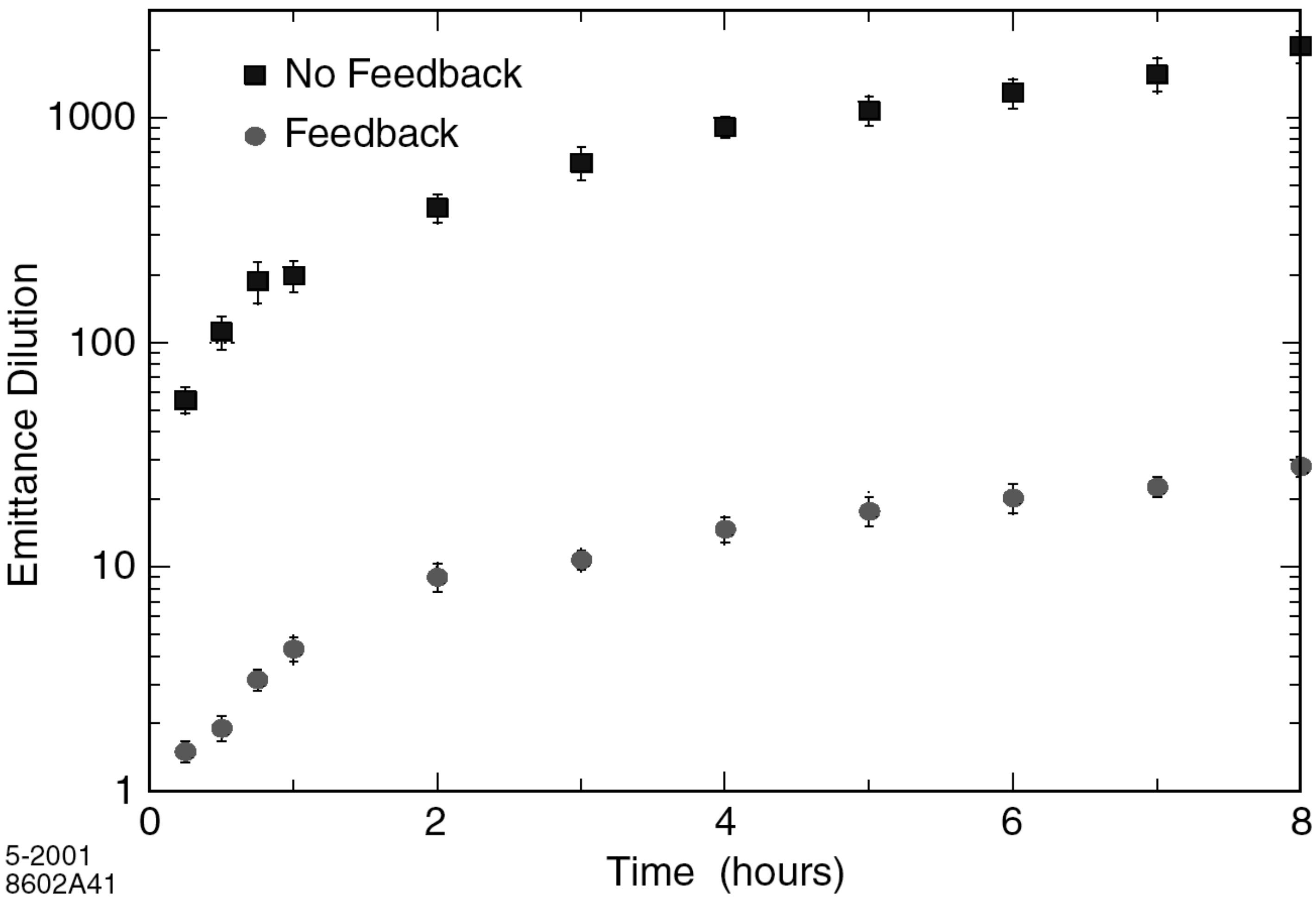
<1nm resolution demonstrated at UBC and SLAC



J. Frisch, SLAC, LC’02

Threats to luminosity from the motion of components

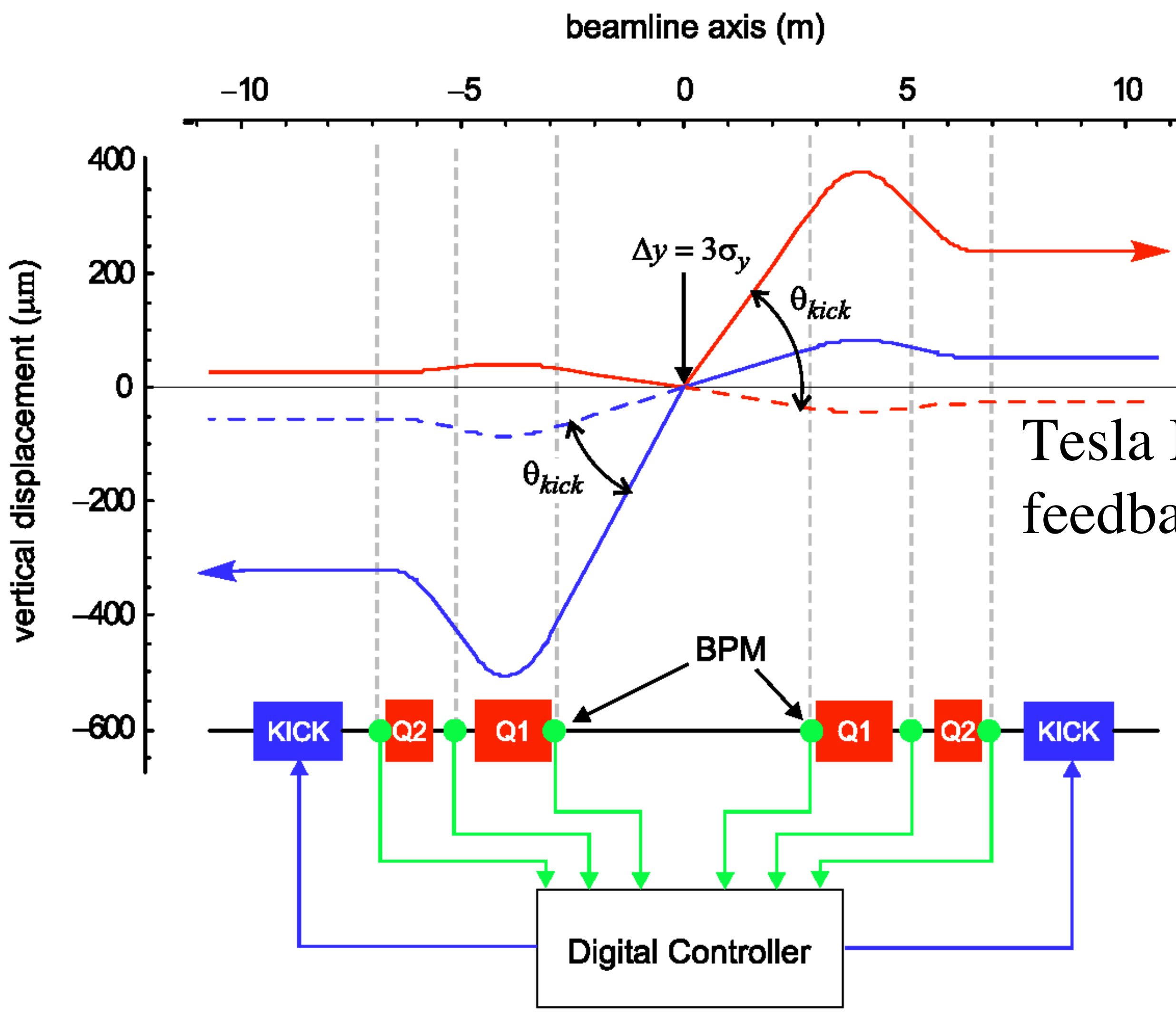
- At very low frequencies (hour-day-month time scale), ground motion is diffusive:
- ATL law: $\Delta x^2 = A*t*l$: amplitudes can be large.
- A varies from 10^{-5} to $\sim 10^{-7}$ $\mu m^2/(m\text{-}s)$, depending on the site
- May also have systematic long term motion such as settling.
- This large amplitude motion can cause misalignments to develop, leading to emittance dilution. It requires periodic realignment. The time between (invasive) realignments can be increased by the use of steering feedback.



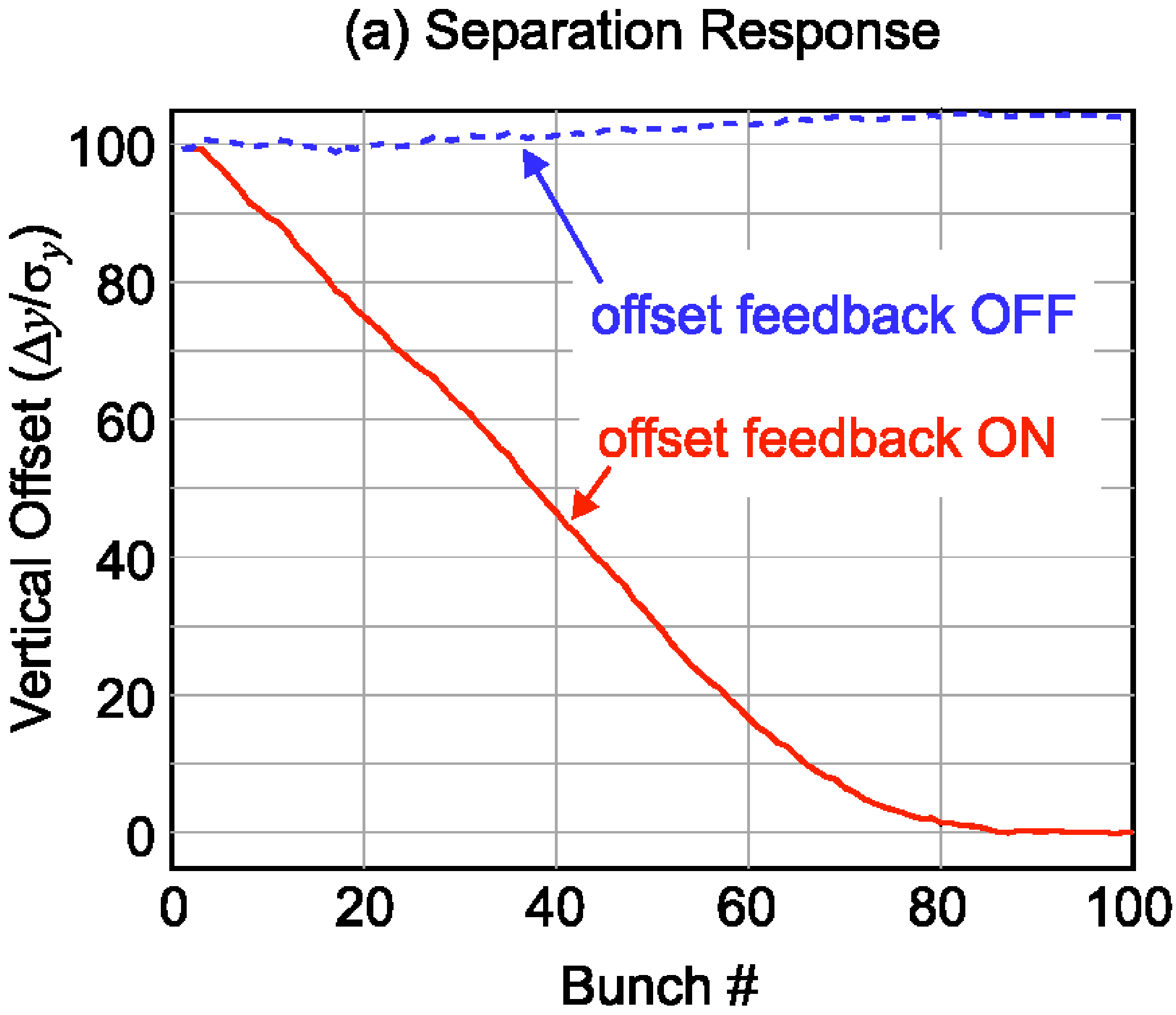
From NLC Snowmass report: emittance growth in the presence of ground motion, with and without linac steering feedback

Feedback at the IP

- The beam-beam deflection is a sensitive indicator of an offset at the collision point.
- Feedback systems based on this fact can provide powerful beam jitter correction over a broad frequency range.
- This method is particularly well suited for TESLA, because of the large bunch separation, but is also planned for the NLC.



Tesla IP fast feedback)



TESLA
TDR

TESLA IP fast feedback correction

Additional issues

- Spin rotation and bunch compression
- Chromatic correction and bandwidth of the final focus
- Collimation and beam halo
- Reliability, availability, and machine protection

NLC Bunch Compressor

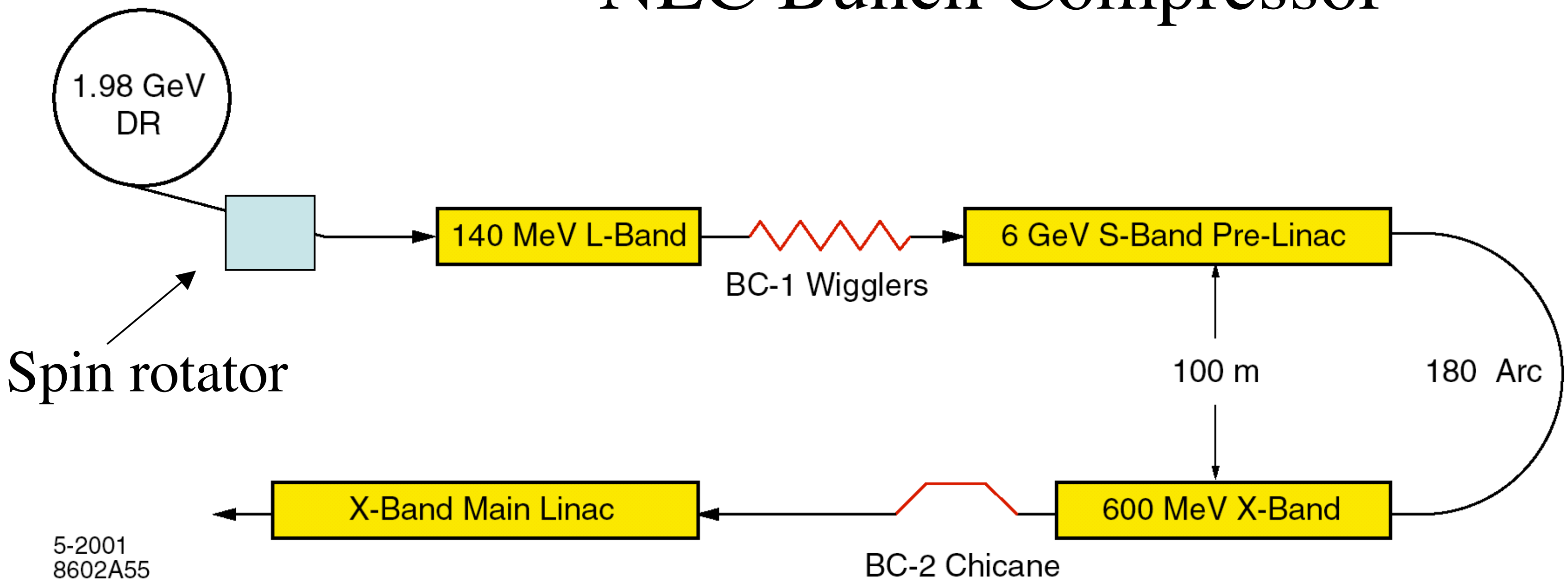
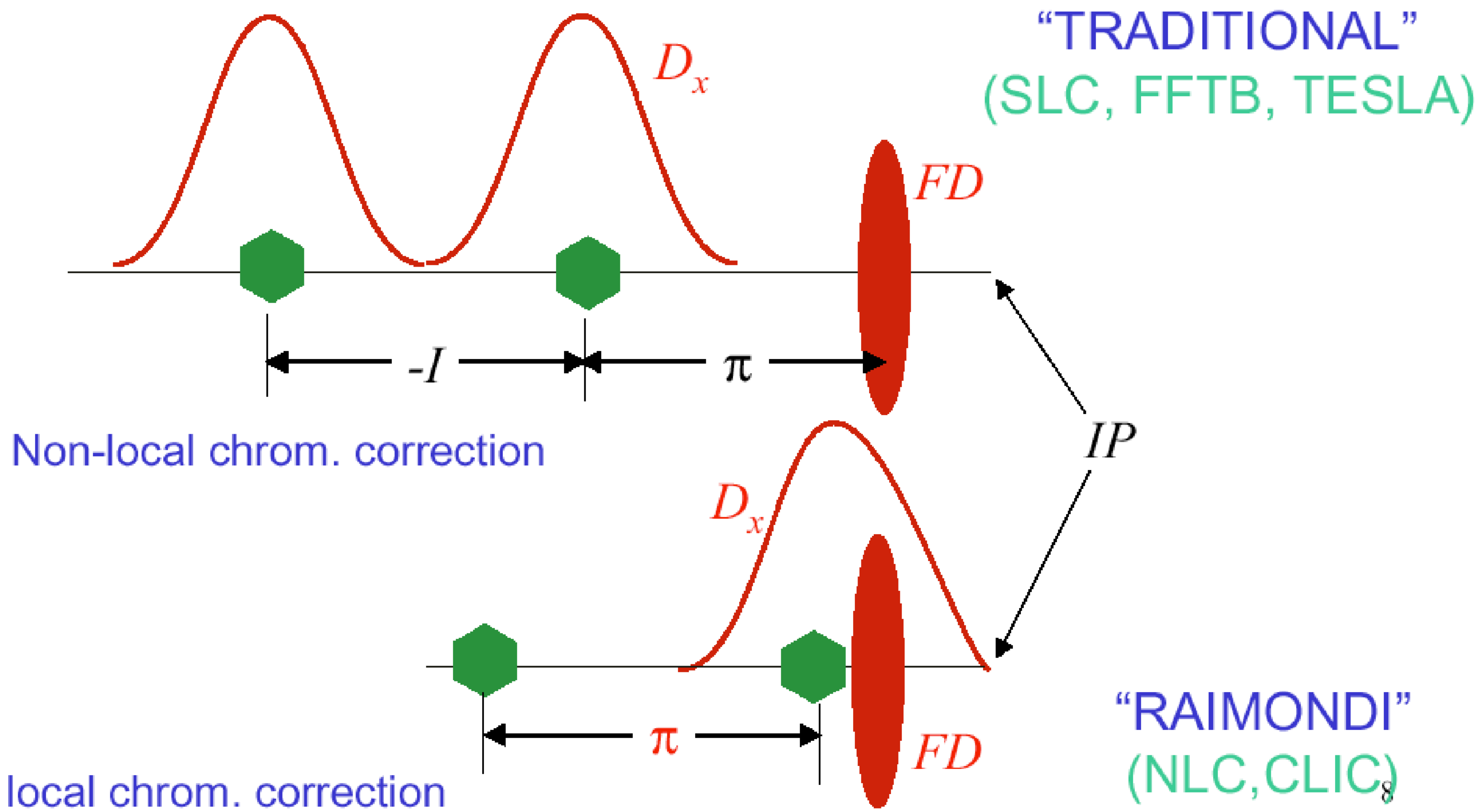


Figure 5.7: The NLC two-stage bunch length compression system. The first stage of compression consists of an L-band rf section followed by a dipole wiggler, operating and 1.98- GeV. The second stage of compression includes the 6-GeV prelinac, 180° turn-around arc, a 600-MeV X-band rf section and a dipole chicane. Beam diagnostics are included to permit full tune-up and control.

Bunch compressors-issues

- Emittance growth in the bunch compressors can result from
  - Misalignments-particularly where the energy spread is large
  - Chromatic aberrations in the dispersive elements
  - Coherent and incoherent synchrotron radiation.
    - CSR will produce a correlation between longitudinal position and transverse position, similar to the effect of short-range wakefields.

LC Chromatic correction schemes



N. Walker

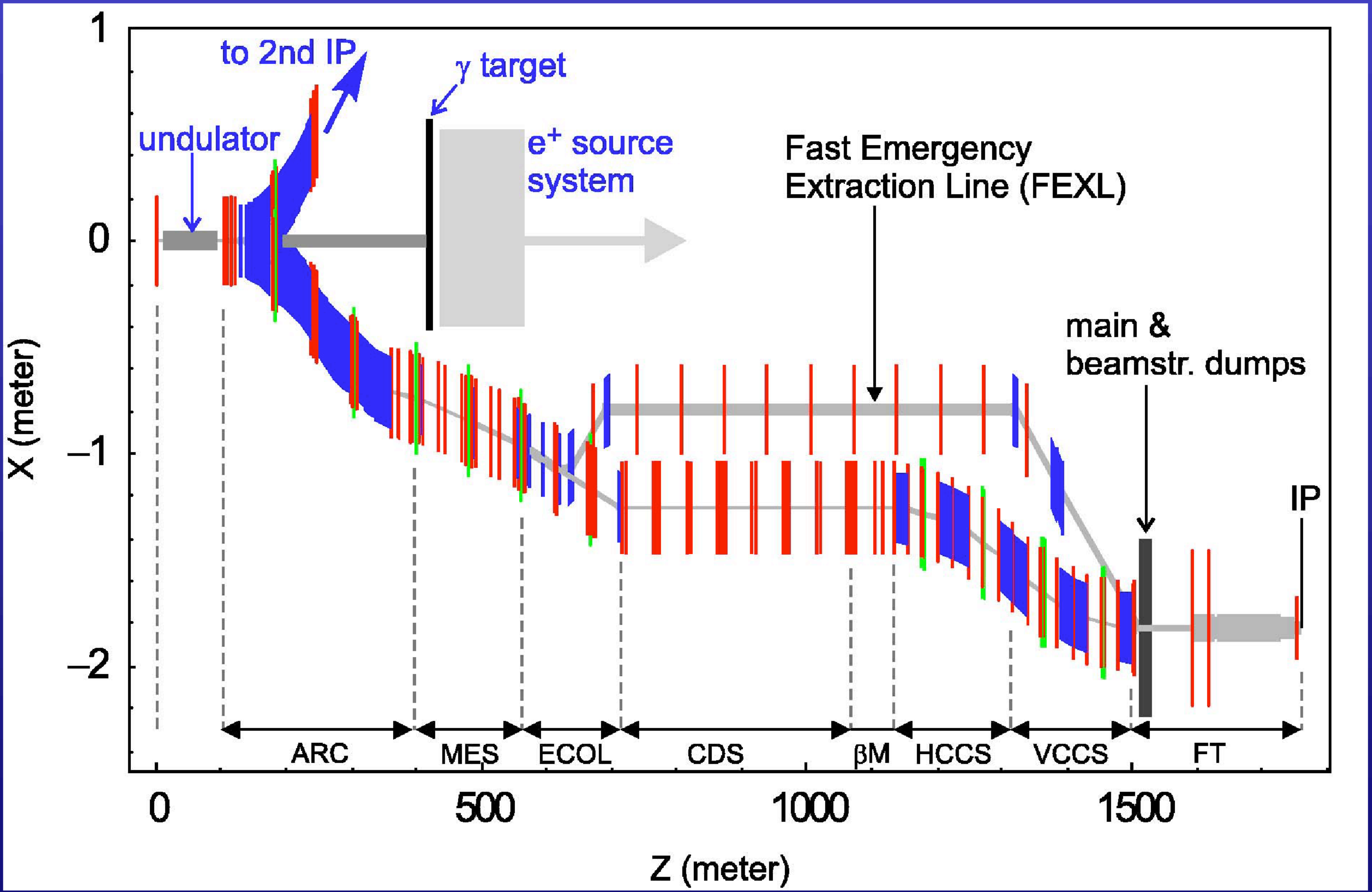
Collimation and beam halo

- All machine designs remove beam halo to the “collimation depth”: that depth for which SR photons generated in the IR pass cleanly through the IP. This is done using pre-linac, and post linac momentum and betatron collimation.
- Mechanical collimators remove the beam halo by physical interception on a thick absorber. Collimation “efficiency” is typically 10^{-4} to 10^{-5}. NLC also uses “octupole folding”.
- The absorber is shadowed by a “spoiler” to protect it from a direct hit by the beam.
- Muon background from the collimated halo must be controlled with “muon spoilers” (e.g., magnetized toroids in the tunnel).
- Close passage of the beam by a collimator can produce emittance growth and jitter amplifcation due to collimator wakefields

Reliability, availability, machine protection

- Reliability studies are just beginning to begin in a serious way. Target availability for the NLC: 85%.
- Machine protection is coupled strongly to the halo collimation system, as this is the design limiting aperture.
- TESLA can use a fast extraction system for machine protection; NLC uses “consumable” spoilers

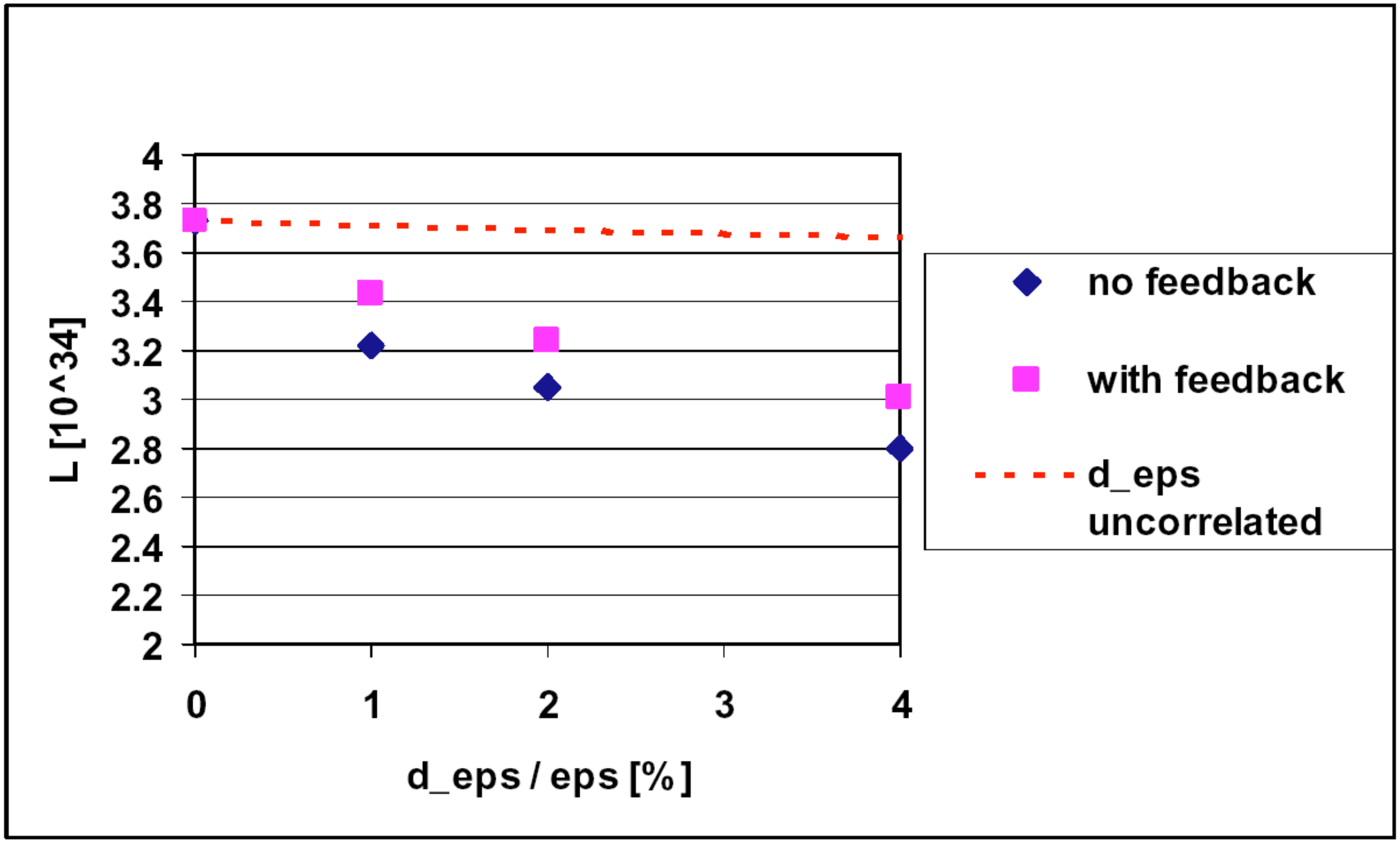
BDS Layout


to 2nd IP
γ target
undulator
e+ source system
Fast Emergency Extraction Line (FEXL)
main & beamstr. dumps
IP
1
0
–1
–2
X (meter)
ARC
MES
ECOL
CDS
βM
HCCS
VCCS
FT
0
500
1000
1500
Z (meter)

Additional issues

- Beam-beam effects:

  If the beam-beam disruption is large, residual correlations between vertical and longitudinal position in the bunch (from transverse wakefields) can be dynamically amplified by the beam-beam interaction into a much larger loss of luminosity than one would estimate just from the effective beam size increase.



Dependence of luminosity on correlated emittance, for TESLA

Conclusion

- High luminosity is achieved in current linear collider designs (TESLA, JLC/NLC, CLIC) by a combination of high beam power (~MW) and small beam spot size (~nm).
- Achieving nm scale beam spots requires generating ultra-low emittance beams in damping rings, and transporting the beams to the collision point without significant emittance growth.
- Both of these requirements are very challenging. Current designs, based on experience with SLC and simulations, satisfy the goals, but demand high quality diagnostics, elaborate tuning algorithms, and sophisticated feedback systems.